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Rethink fired heater design for emissions

As environmental regulations are becoming more stringent on reduced nitrogen oxide (NO_x) and carbon monoxide (CO) emissions, burner designs are changing to meet revised regulations. The heater design must complement the chosen burner for optimal performance. Although design duty is considered to be the main focus of the heater design, the range of heater operation and its impact on heater safety and emissions needs are often neglected.

Heater operating range. The heater operating range should be considered at the design phase itself. Typically, burners witness CO breakthrough (increased CO emissions) at bridgewall temperatures (BWT) lower than 1,300°F. Volatile organic compound (VOC) emissions also increase with BWT lower than 1,300°F. In some cases, burner vendors may be willing to guarantee emissions for lower operating temperatures, but it is a case-by-case discussion.[1]

FIG. 1 provides an estimation of the BWT vs. average radiant flux as a function of average tube metal temperature (TMT). The tubes are spaced at two nominal diameters. This specification applies to most operating box and vertical cylindrical furnaces (single fired boxes).

Although the TMT is dependent on the heat flux and fluid dynamics inside, for most operating furnaces, average TMT can be approximated using Eq. 1:

$$T_{avg} = T_{in} + 0.75\ (T_{out} - T_{in}) + 125°F \qquad (1)$$

where:

T_{avg} = Average TMT, °F
T_{in} = Process inlet temperature, °F
T_{out} = Process outlet temperature, °F.

Case Study 1. A new regeneration heater was installed with ultra-low NO_x burners, as an effort to reduce NO_x emissions. CO and combustibles analyzers were added as a part of the safety upgrade.

When the heater was operated, high CO emissions were recorded. It was realized that the heater datasheet listed only the design case (higher-duty case), which was considered as a design basis; however, when the heater was operated at normal loads (greatly reduced duty) it resulted in a cool box, which contributed to high CO emissions. The heater was re-permitted, and reduced load emissions guarantees were obtained from the heater and burner vendors.

HEATER OVERDESIGN

When designing a new unit, extra design margins are typically added to the entire process (increased process duty, process flow, etc.) as an insurance to meet or exceed the guarantees provided. Excessive margins can be problematic for heater designs, as this results in excessive burner overdesign and heater turndown requirements. Excessive overdesign can cause problems in designing heaters and burners to meet emissions at turndown (BWT lower than 1,300°F promote high CO and VOC emissions). When excessive heater overdesign is observed, it should be discussed with the client or the process licenser to ensure that they are aware of the limitations.

Case Study 2. A hot oil heater with a selective catalytic reduction (SCR) system was specified with 120% overdesign to meet design guarantees, which resulted in a much lower turndown requirement. This resulted in low radiant box temperatures (BWT). The specified hot oil had a low process outlet temperature, with considerable margin in maximum allowable film temperatures.

The average radiant flux was increased, and a turndown emissions guarantee was obtained for 1,250°F BWT. In this scenario, the process film temperatures could accommodate higher temperatures (without affecting the desired heater run length), with the increase in average radiant flux to achieve the required process and emissions guarantees at turndown.

Common burner types. The burner is the heart of the heater, where combustion occurs. Burner selection is extremely critical

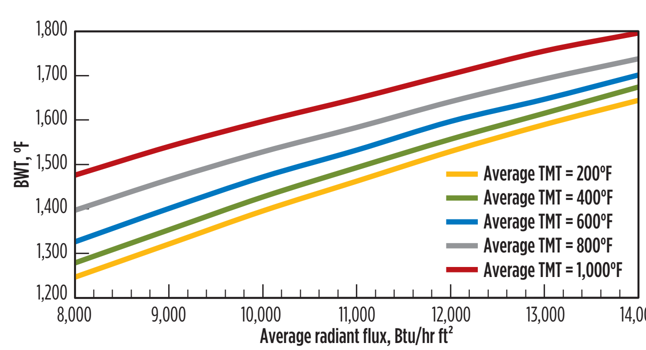

FIG. 1. Estimation of BWT as a function of average TMT and average radiant heat flux (tubes spaced at two nominal diameters) for single fired boxes.

for heater design, safety and emissions. Some common burner types are listed in the following subsections.

Premix gas burners work with the primary air and fuel gas mix upstream of the burner discharge, before combustion occurs. Kinetic energy of the fuel is utilized for mixing. These burners are characterized by short, tight flames. However, these burners have limited turndown due to flashback concerns.

In **raw gas burners,** the gas and the combustion air do not mix until they leave the discharge ports, which eliminates the flashback concerns of premix burners. Therefore, raw gas burners have good turndown capability. These burners are typically characterized by a single tip with discharge ports.

Low NO_x burners use staged air or staged fuel for staged combustion and reduced peak flame temperature. This burner technology utilizes some flue gas recirculation and results in longer flames, when compared to a premix or a raw gas burner.

Ultra-low NO_x burners (ULNB) utilize increased flue gas recirculation (cool flue gases at the heater floor) with staged fuel (as much as 90% fuel staged to secondary tips). Combustion is delayed, which results in much longer flames and reduced NO_x emissions. These flames are more dependent on the radiant box flue gas recirculation currents for proper combustion and flame shape. A computational fluid dynamics (CFD) study of the radiant box is highly recommended when considering the ULNB technology. A detailed burner test(s) should be considered with CO probing (for determining flame boundary/dimensions) at the vendor's facility for the burner operating range.

TYPICAL HEATER EMISSIONS

Several types of heater emissions should be considered, as listed in the following subsections.

NO_x emissions. Oxides of nitrogen are typically formed through thermal and fuel NO_x (mainly NO and NO_2 emissions). Air staging, fuel staging and increased flue gas recirculation are common ways to reduce NO_x emissions. In special circumstances, steam injection is used to reduce NO_x. Post-flame treatment methods to reduce NO_x include the use of SCR or, in some special cases, selective non-catalytic reduction (SNCR) technologies.

CO emissions. Incomplete combustion or improper mixing of fuel and air will result in increased CO emissions.

VOC emissions. VOCs are typically caused by incomplete combustion. API RP 535[2] defines VOC as any compound of carbon that can participate in atmospheric photochemical reactions.

Particulate emissions. API RP 535 states that all fuels will contain or produce particulates. Some particulates can also result from eroded refractory, tube scales, etc.

SO_X emissions. Sulfur content in the fuel directly contributes to SO_x emissions. SO_x emissions react with water to form sulfuric acid. The best way to reduce SO_x is to reduce the sulfur content of the fuel.

NH_3 emissions. Ammonia (NH_3) slip emissions are caused by the unreacted NH_3 passing over the SCR catalyst. These are to be addressed when an SCR unit is installed with the heater. Typically, CFD is carried out to ensure proper NH_3 distribution.

CO_2 emissions. A byproduct of combustion is CO_2. Higher heater efficiency will produce fewer CO_2 emissions.

Most jurisdictions now require a sub-30-ppm NO_x performance from the fired heaters, with a push for even lower reduced NO_x emissions. As a result, ultra-low NO_x burners have become a standard selection for most fired heater designs.

Design considerations. It is important to consider a few design features for safe heater operation that ensures emission guarantees are met.[3]

ULNB considerations. ULNB are characterized by longer flame lengths. For a properly designed heater and burner, the combustion process should be completed well before the radiant arch (also referred to as the bridgewall). The estimated flame length is 1.5 ft/MMBtu–2 ft/MMBtu. Depending on the burner design and spacing utilized, flame coalescing can increase flame dimensions considerably. The chosen burner flame length should not exceed two-thirds of the radiant box height. Expected flame height should be discussed with the burner vendor and should be accounted for in the required radiant height/coil geometry design.

Case Study 3. An existing box heater was being revamped with ULNB burners to meet reduced NO_x emissions, as an upgrade from installed raw gas burners. When the CFD was conducted, it was realized that the flames coalesced and the box height and floor layout were not adequate for the increased flame dimensions. A multiple-row burner layout with staggered rows was considered. A multi-burner test was conducted at the burner test facility to ensure that flame dimensions and all emissions guarantees were being met.

Radiant box geometry. Radiant box geometry substantially influences the ULNB flame shape and stability. Asymmetrical boxes can have odd flue gas recirculation, which can adversely affect the ULNB flame shape, stability and performance.

Case Study 4. An existing twin cabin heater with a common convection section and premix gas burners was retrofitted with ULNB to reduce emissions. When the heater was operated, the flames bent on one side of the box and impinged on the tubes, causing high tube metal temperatures and restricting the heater duty. It was realized that the slant on the top of the radiant section, coupled with a side exit for the common convection, caused the flue gases to recirculate at the top of the heater, thereby pushing the longer flames on the tubes. CFD was conducted, and the floor was redesigned with forced-draft burners to reduce flame height.

Tube layout. Tube layout should be evaluated before selecting the type of burner. Tube layouts can cause asymmetrical flue gas patterns that can adversely affect the burner performance.

Case Study 5. A client retrofitted new ULNBs with originally supplied raw gas burners for a reheat furnace with arbor coils (inverted U-coils) to reduce NO_x emissions. When the heater was fired up, all the flames leaned to one side, impinging on the tubes and restricting heater operation. A field visit showed that the furnace created asymmetrical flue gas patterns due to hot-end and cold-end tube walls (i.e., the process entering one cold-wall side manifold and exiting the other hot-wall side manifold). Considering the box size and the extra cushion in the NO_x emissions guarantees, the floor was redesigned and replaced with a center wall and flat flame burners. This redesign solved the problem.

Burner layout and spacing. Inadequate burner spacing promotes flame-to-flame coalescing and increases flame dimensions in field operation, which results in higher NO_x emissions. As a general rule, a minimum burner-to-burner spacing should be equal to the flame diameter (estimated at two times the burner throat diameter). It is important to realize that flame-to-flame coalescing can result in greatly increased flame dimensions in the field. The final layout should be discussed with the burner vendor to ensure that guarantees are being met.

As a minimum, the burner layout should meet all API RP 560 specified clearances. It is generally recommended to add a 6-in. or greater margin for burner-to-tube spacing. The layout can be a single row or multiple rows for box heaters, or a single circle or two circle for a vertical cylindrical heater. Single-row or single-circle burner layouts are preferred for new designs. With multiple-row or two-circle layouts, flue gas recirculation to the inner burners becomes problematic and can increase NO_x emissions. When dealing with retrofits or heater revamps on existing furnaces, however, all options may need to be considered due to the existing layout or plot space constraints.

Case Study 6. A vertical cylindrical heater with ULNBs was commissioned and started up. As the heat duty was increased, the flames collapsed on the tubes. It was realized that the burner circle diameter was large, which led the flue gases to rise and develop a downward flow through the center of the radiant box inside the burner circle. This, in turn, pushed the flames on the tubes. A CFD study was conducted for the radiant box, and the burner circle diameter was rearranged to address the problem.

Case Study 7. An operator was adjusting the stack damper from the control room. He accidently entered a wrong input, which resulted in the sudden closure of the stack damper (with large movement from its initial position). This created a pressure surge in the box and took out the burner flames and the pilots. No incident occurred. Flame scanners were installed later as safeguards.

Note: Many incidents have occurred in heaters, due to sudden adjustments made to the heater draft. Draft is created due to the differential densities between the cold air and the rising hot flue gases. Draft is negative pressure inside the furnaces, which is required to inspirate the air through the burners to ensure proper combustion.

FIG. 2 shows the sensitivity of the burner performance when sudden changes in draft occur. Shown are an operating floor draft and a corresponding set of draft change curves to indicate how much excess air change (%) will occur in the natural-draft burner when a corresponding draft change (as shown in the curves) is made. The heater is operating at 15% excess air. The graph indicates that shorter boxes are much more sensitive to draft changes than taller boxes. Although the burner may hold flames at sub-stoichiometric conditions, most burner vendors may not provide any flame assurance once the burner reaches stoichiometric conditions. Unstable burners can witness flameout even at higher-than-stoichiometric conditions.

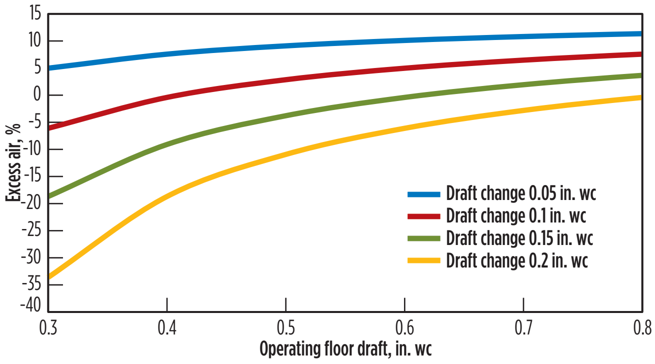

FIG. 2. Air change (%) in a heater as a function of draft changes (heater operating at 15% excess air) for natural-draft burner.

The burner vendor should be consulted on the burner stability range for the specific application with alarm and trip point recommendations. It is typically not advisable to operate heaters with less than 10% excess air.

Floor draft can be estimated using Eq. 2:

$$D_{Floor} = 0.01 \times H_{Rad} + D_{Arch} \tag{2}$$

D_{Floor} = Operating floor draft, in. wc.
H_{Rad} = Radiant box height, ft
D_{Arch} = Draft at radiant arch, in. wc.

In practical operation, the bridgewall drafts are seen to vary in the range of 0.1 in. wc–0.15 in. wc.

Burner overdesign. The burner should be designed with reasonable overdesign. API RP 560 defines these requirements. However, it has been observed that in some cases, the burners are greatly overdesigned, which directly impacts the flame shape and stability.

Case Study 8. An operating heater was reported to have issues with tall, lazy flames impinging on the tubes. A study indicated that burners were designed for forced-draft operation with 125% burner duty requirement in natural-draft operation, to accommodate multi-burner maintenance due to fuel gas quality issues. Poor design of air plenum resulted in severe maldistribution to all burners. Burners were changed to higher-pressure-drop burners, with reduced duty in natural-draft operation. A CFD was conducted on the air duct arrangement with restriction orifices to address air flow misdistribution. This resulted in tight and short flame burners, which addressed the field issues.

Fuel gas quality. ULNBs have multiple burner tips with small orifices that are prone to plugging. Fuel gas conditioning should be utilized to minimize operator maintenance and burner downtime. This is especially important if refinery fuel gas is utilized. As a minimum, the following guidelines should be observed:

- Strainers upstream of the trip valves provide assurance that the trip valves will have a tight seal when the heater is shut down.
- Coalescers should be considered if there is a possibility of liquid carryover to the burners. Knockout drums should be designed adequately to capture the liquid slugs.
- If the fuel gas lines have heavies that can potentially condense and cause liquids to carry over to the burners, heating of the fuel gas may be considered.
- Heat tracing with insulation may be considered between the fuel gas heater and the burners. When insulation is used, corrosion under insulation should be evaluated.
- Depending on the fuel gas composition, a fuel gas piping metallurgy upgrade should also be considered from the coalescer to the burners.

Note: The range of refinery fuel gas compositions (light, average and heavy) should be specified to ensure that the burner is stable and the flame dimensions and emissions are met for the entire range of fuel gas heating values.

Case Study 9. Burners were reported to be exceeding the burner capacity curve. The heaters utilized ULNBs with refinery fuel gas. A study of the heaters indicated that although the heater was operating within its design capacity, the burners were severely plugged. Nearly one-third of the burners were on a constant maintenance burner cleaning schedule, which resulted in over-firing of the other burners to meet process demands. Fuel gas conditioning and a piping upgrade were implemented to address the issue.

Radiant floor heat density. An important parameter when considering the heater floor design with ULNBs, the radiant floor heat density is calculated as the design heat release divided by the tube circle area (for vertical cylindrical heaters), or the box area confined by the tubes (length × tube-to-tube width). Optimal floor heat density is less than 200,000 Btu/hr/ft^2. However, some vendors consider maximum allowable floor densities between 300,000 Btu/hr/ft^2 and 400,000 Btu/hr/ft^2, which can be common in retrofit applications. Higher floor densities increase the potential of flue gas plug flow in the radiant section, with inadequate flue gas recirculation to the burners. This increases NO_x and results in poor flame patterns.

Case Study 10. A client retrofitted an old vertical cylindrical heater with ULNBs. When the heater was operated, flame patterns were not uniform. A CFD study indicated that, due to slender box design with L/D > 3 and high floor heat density, the flue gases witnessed a plug flow with inadequate recirculation to the burners. The burners were redesigned with forced-draft operation to address the issue.

Air leakage. Ideally, all excess air measured should come through the burners to ensure that burners are getting the required air for proper combustion. Air leakage from the tube penetrations also results in increased oxidation and higher thermal stresses. Air leakage through the furnace should be minimized. It is recommended to install boot seals on all process tube penetrations, tube guides, the caulk radiant and convection sections.

Case Study 11. Burners were reported to be highly unstable. An inspection of the heater indicated that a few burners had air registers stuck open and were not being operated. This resulted in high leakage of air through the burners, thereby completely starving the operational burners of air. Air registers were made operational and closed for non-operational burners, resolving the stability and flame pattern issues.

Heater efficiency and BWT. BWT increases with the utilization of ULNBs, which results in a slight loss of heater efficiency. Efficiency loss can vary depending on the furnace design parameters, and should be evaluated and considered in the

heater design. Since all burner emissions are based on the BWT, accurate temperature measurement is required at this location.

BWT measurements using convection thermocouples are sometimes found to have an error margin as high as 200°F–250°F, due to the location and the re-radiation from the surrounding cold surfaces. Shielded velocity thermocouples should be considered in the radiant bridgewall sections for accurate temperature measurement. A shielded velocity thermocouple is basically a shielded stainless steel tube (1 in.), which shields the thermocouple from cold surfaces. A velocity thermocouple has an air connection that creates a vacuum for induction in an actual flue gas sample, and the sample is measured through the thermocouple.

Note: Radiant floor temperatures can vary with the furnace design; however, typically they can be estimated in a range of 200°F–300°F lower than the BWT.

SCR considerations. NO_x reduction from the burners has limitations. As the combustion is delayed, the flame becomes longer and more dependent on the radiant flue gas currents. Although new advancements in burner technology are working to achieve extremely low NO_x numbers, the proposed burner technology for NO_x reduction should be closely evaluated and considered with the heater design. For reduced NO_x requirements, most commonly utilized post-combustion NO_x control technology is an SCR. Typically, SCR technology is preferred over SNCR due to higher NO_x reduction capability (upto 95% reduction) and tighter ammonia slip (NH_3 emissions). SNCR requires high operating temperatures to be effective for the operating range. This limits the use of SNCR to specific applications.

The following design features should be considered with an SCR:

- Depending on the sulfur content of the fuel, at low flue gas temperatures, salt formations (ammonium sulfate and ammonium bisulfate) can occur due to NH_3 reacting with sulfur (SO_3). This can plug up the SCR catalyst. Very high flue gas temperatures can result in SCR catalyst damage (sintering). Salt formation temperatures and sintering temperatures should be carefully evaluated, and the SCR operating temperature range may need to be adjusted for trouble-free operation.
- Possible SCR catalyst poisons in the fuel/flue gas should be evaluated and discussed with the SCR supplier.
- It is recommended to have castable refractory in the convection and duct sections, as these sections witness higher flue gas velocity. Flaking of the ceramic fiber from the convection has resulted in plugging of the SCR sections.
- A CFD of the NH_3 distribution in the flue gas duct and across the SCR should be considered. Inadequate distribution will result in shortened catalyst life and increased NH_3 emissions.

If an air preheater is considered, special consideration should be given to dewpoint issues at the cold end. Cold air bypass or air preheating are common methods to prevent cold-end dewpoint issues. In special circumstances, borosilicate glass tube design at the entry section is used to address the cold-end dewpoint issues.

When utilizing the air preheater with an SCR unit, a water wash or other cleaning considerations should be provided for salt cleaning.

Case Study 12. An induced-draft (ID) heater was installed. When the heater was operated, an ID fan damper control was found to be inadequate. A CFD study showed that the flue gas patterns entering the ID fan were not uniform, thus causing inadequate control. Turning vanes were added in the flue gas duct to address the issue.

CO catalyst considerations. Ideally, the heater operating range is designed to be well within the NO_x, CO and VOC emissions guarantees. However, certain process restraints can result in turndown scenarios where CO or VOC emissions can increase, and CO catalyst may need to be utilized to meet environmental constraints.

CO oxidation catalyst can be utilized to reduce CO or VOC emissions. However, it is important to realize that a CO oxidation catalyst reacts actively with NH_3 and results in oxidation of NH_3 to NO_x. When utilizing CO catalyst in a system with SCR catalyst, typically the CO catalyst will be placed upstream of the NH_3 injection grid, so that the NH_3 does not react with CO catalyst to increase the NO_x emissions, which will result in a bigger NO_x catalyst and a bigger ID fan to encounter higher pressure drop, which results in higher operating cost. However, if CO catalyst is placed downstream of the NH_3 injection, then SCR catalyst should be sized to account for increased NO_x emissions.

Case Study 13. A heater with an SCR system was designed with space for future CO catalyst. The client was witnessing CO emissions issues and wanted to add a CO catalyst to meet the emissions permit. However, when a check was done before installation of the CO catalyst, it was realized that the original design accounted for increased pressure drop in the ID fan from CO catalyst. However, it did not account for increased NO_x emissions from CO catalyst, with the CO catalyst location downstream of the NH_3 injection grid.

Due to the extra pressure drop margin available in the ID fan, the injection grid was located downstream of the CO catalyst, and a pressure drop plate was added for uniform NH_3 distribution over the SCR catalyst. A CFD was conducted, and the issue was resolved. HP

NOTE

All case studies presented here have been developed solely for the purpose of illustrating typical problems and their solutions. Their resemblance to any real installation may be coincidental.

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